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NASA
Technical
Paper
2493

July 1985

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SUMMARY

The problem of mixing aircraft equipped with time-controlled guidance systems and unequipped aircraft in the terminal area has been investigated via a real-time air traffic control simulation. These four-dimensional (4D) guidance systems can predict and control the touchdown time of an aircraft to an accuracy of a few seconds throughout the descent. The objectives of this investigation were to (1) develop scheduling algorithms and operational procedures for various traffic mixes that ranged from 25% to 75% 4D-equipped aircraft; (2) examine the effect of time errors at 120 n. mi. from touchdown on touchdown-time scheduling of the various mix conditions; and (3) develop efficient algorithms and procedures to null the initial time errors prior to reaching the final control sector, 30 n. mi. from touchdown. Results indicate substantial reduction in controller workload and an increase in orderliness when more than 25% of the aircraft are equipped with 4D guidance systems; initial random errors of up to ±2 min can be handled via a single speed advisory issued in the arrival control sector, thus avoiding disruption of the time schedule.

INTRODUCTION

On-board guidance systems that can predict and control the touchdown time of an aircraft to an accuracy of a few seconds throughout the descent have been proposed as an element of a future air traffic control (ATC) system (refs. 1 and 2). The feasibility and performance of such systems, also known as four-dimensional (4D) guidance systems, have been demonstrated in several flight test programs (refs. 3 and 4).

A crucial problem in the application of 4D guidance is the development of ATC procedures that can exploit the on-board time-control capability. The use of a time-based scheduling system in the terminal area for all 4D-equipped aircraft was investigated in an earlier real-time simulation study (ref. 5). That study demonstrated that when using all 4D-equipped aircraft in the system, operational procedures and scheduling techniques could be developed that would reduce delays and increase the capacity of the time-based system relative to that of a vectoring mode by a significant amount.

However, in planning for a future system involving a majority of 4D-equipped aircraft, it is necessary to consider the transition situation in which some percentage of traffic must still be controlled by conventional methods. The basic difficulty is that the 4D concept involves a separation of aircraft by time, yet in the conventional vectoring mode, the controllers provide distance separation. Developing techniques to handle both types of aircraft effectively is a complicated task. A simple, though inefficient, way to handle both types of scheduling techniques is (1) to schedule, by time, the 4D-equipped aircraft using methods developed earlier, and (2) for each vectored aircraft, assign a large time slot (e.g., 10 min) so that a controller can deliver the aircraft to the scheduling point within the allotted slot. The difficulty with this method is that these large time slots can reduce capacity so that operating in the mixed mode is less efficient than operating in a pure vector mode. A necessary constraint in the development of the mixed mode is that it must not result in decreased capacity for the total system.

Another constraint is that the advantages achieved by the 4D-equipped aircraft must not be achieved at the expense of the aircraft being vectored by conventional procedures; that is, vectored aircraft must still be given a reasonable number of clearances, and they must not be delayed more than they would be when all aircraft are being controlled conventionally. Hence, the objective of this study was to develop efficient algorithms and operational procedures for time scheduling a mix of 4D-equipped and unequipped aircraft in the terminal area. To aid in accomplishing this task, a real-time ATC simulation was conducted in which an extended terminal area was considered. Aircraft entered the extended terminal area at cruise altitude at feeder fix points about 120 n. mi. from touchdown. In some of the runs, touchdown-time errors for unequipped aircraft were based solely on the buildup of errors when they operated within the extended terminal area, assuming they left the feeder fix at the specified time. To account for errors in the time that may occur at the feeder fix, in the remainder of the runs, unequipped aircraft were given random feeder fix departure errors ranging from +2 min to -2 min. A speed advisory system was developed to aid the controllers in meeting the assigned touchdown times and thus nullifying the initial departure errors.

The on-board 4D system will be described and the problems associated with time scheduling a mix of 4D-equipped and unequipped aircraft will be discussed. This will be followed by a description of the simulation facility, scenario, and test conditions. Simulation results will then be presented.

This study is part of a joint program of real-time simulations using facilities at the NASA Ames Research Center, Moffett Field, California, and at the Federal Aviation Administration (FAA) Technical Center in Atlantic City, New Jersey. Previous studies in the joint program have included delayed-flap and profile-descent fuel-conservative approaches, helicopter instrument flight rule (IFR) arrival operations into major terminals, and procedures for controlling short takeoff and landing (STOL) aircraft in a high-density terminal area (refs. 5-8).

ON-BOARD 4D SYSTEM

Overview

A complete 4D guidance system is a complex entity involving interaction between numerous guidance, control, and navigation subsystems in an aircraft. The integrated collection of these subsystems augmented with special algorithms to provide fuel-efficient time control essentially constitutes the 4D flight management system of an equipped aircraft.

For a number of years NASA has designed and flight-tested research systems incorporating various types of time control methods for both STOL and conventional aircraft. These tests have demonstrated the ability to predict and control arrival time accurately under varied operational conditions, achieving arrival time accuracies of ±10 sec (refs. 3 and 4).

The system simulated in these studies comprises algorithms and techniques previously flight-tested (ref. 9) as well as new techniques developed specifically for these studies. The discussion here centers primarily on the techniques unique to the current study.

The on-board calculation of a 4D trajectory is carried out at the time the aircraft departs the feeder fix, located approximately 120 n. mi. from touchdown, and at a cruise altitude of 33,000 ft. The calculation is initiated when the simulated on-board system receives specification from the pilot of touchdown time and approach route. If the flight/performance envelope of the aircraft permits, the system will generate a time-controlled approach trajectory starting at the current location of the aircraft and terminating at touchdown. Inability to meet the specified time causes the system to display an error message at the controller and/or pseudopilot positions.

The successfully synthesized trajectory consists of a vector function of time whose components are reference values of x and y positions, altitude, heading, and airspeed. Immediately after the trajectory has been synthesized in fast time, it is regenerated in real time, to provide continuously updated reference states. The equipped aircraft tracks the reference trajectory by means of a closed-loop autopilot guidance law, which enables the aircraft to complete the approach trajectory within a few seconds of its ATC-assigned time.

The problem of synthesizing such trajectories is divided into three subproblems solved sequentially. First, the horizontal profile is constructed as a sequence of circular arcs and straight lines passing through the set of waypoints that define the approach route (ref. 10). Second, the vertical profile is synthesized as a sequence of level-flight and constant-descent segments passing through specified altitude waypoints located on the horizontal profile. An alternative to the constant-descent-angle profiles are idle-thrust descents which come closer to a fuel optimum status. However, pilot preference is somewhat divided between these two strategies. Finally, the airspeed profile is synthesized to achieve the specified arrival time. Since the speed profile algorithm was developed specifically for this study, it is discussed in greater detail here.

Speed Profile Synthesis

Three types of airspeed profiles typical of those used in the simulation are illustrated in figure 1. All three profiles start at waypoint 5 (WP5) at a cruise altitude of 33,000 ft and at a true airspeed (TAS) of 460 knots, or 280 knot calibrated airspeed (CAS). Constant Mach segments are not shown in these example profiles. The profile labeled "nominal" starts with a brief segment of deceleration to a CAS or Mach number computed by the speed selection algorithm. The computed CAS of 265 knots is held constant during the remainder of the cruise altitude and the greater portion of descent until the 10,000-ft altitude is reached at WP4. A descent at a constant CAS produces the gradual TAS deceleration seen in figure 1. This type of nominal speed profile is typical in airline operations because it can be flown by a pilot using standard cockpit instruments. At 10,000 ft (WP4) the nominal trajectory decelerates to a maximum CAS of 250 knots, in accordance with ATC rules. The 250 knots CAS is held to a point at about 20 n. mi. from touchdown (WP3) where a deceleration to 180 knots occurs. At 5 n. mi. from touchdown (WP2) deceleration to the final approach speed occurs with the flaps extended to the landing configuration. The maximum speed profile shown in the example initially exceeds the speed limit of 250 knots CAS below 10,000 ft. The algorithm allows the speed to be exceeded with prior approval of the flow controller, who is monitoring the flow of traffic into the terminal area.

The time to traverse the path and the points where speed changes begin and terminate are obtained by numerically integrating the following two equations along the known three-dimensional profile:

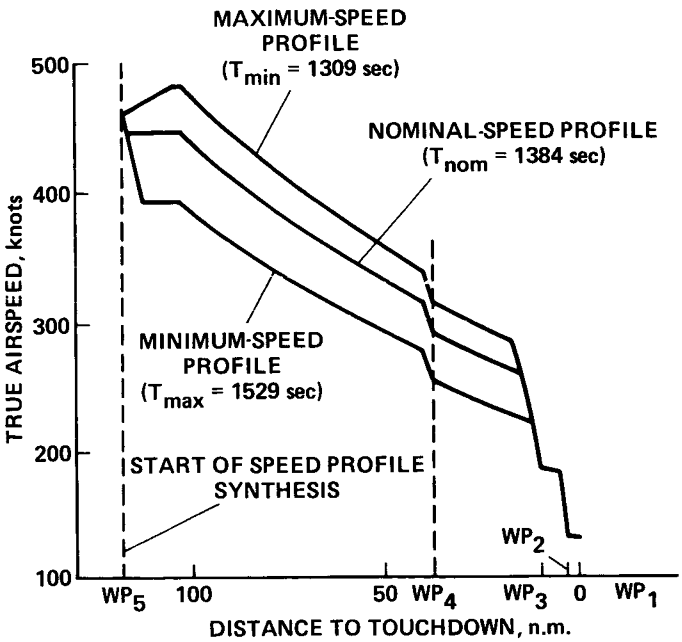


Figure 1.– Controlled time-of-arrival speed profiles.

$$dV_a/dt = (T - D)/W - g \sin \gamma \tag{1}$$

$$dS/dt = V_g \tag{2}$$

where V_a = TAS, T = total engine thrust, D = drag force, W = weight, g = acceleration of gravity, γ = flightpath angle, V_g = ground speed, and S = distance along the flightpath. The integration computes the distance and the time to fly the initial acceleration or deceleration segment, and the constant CAS/Mach number descent in forward time. It computes in backward time, starting at the touchdown point, corresponding quantities for the deceleration segments at the end of the trajectory. The forward-backward integration scheme ensures that the initial and final speeds are achieved at specified speed waypoints along the horizontal profile. Furthermore, numerical integration of equations (1) and (2) allows complete freedom in the choice of models for the thrust T and drag D. In the simulation thrust, drag, and fuel-flow models for a 727 aircraft were used.

The value of thrust used in each integration step depends on the segment type. For acceleration the thrust is set to its maximum and for deceleration it is set to idle. For constant CAS or constant Mach number segments in descent, the thrust computation is more involved; explicit relations for these cases are derived in reference 10. In general, the thrust will be close to the idle value for the 3° descent angle typically used here.

The algorithm for determining a speed profile starting at WP5 with a specified time to fly begins with the synthesis of three profiles flown at maximum, minimum, and nominal speeds: V_{max}, V_{min}, V_{nom}, respectively (see fig. 1). The nominal speed profile is one that the pilot would choose in the absence of any time constraints. By the backward-forward integration procedure just described, the corresponding times to fly, T_{min}, T_{max}, T_{nom}, are obtained. Then a test is performed to determine if the specified time, T_d, falls within the range (T_{min}, T_{max}). If such is the case, a polynominal approximation is computed of the exact but unknown relation between descent speed and time to fly.

$$V = C_1/T + C_2/T^2 + C_3/T^3 \tag{3}$$

A simple proportional formula also allows equation (3) to determine the speed between WP4 and WP3. The details of this procedure are given in reference 10. The coefficients C_1, C_2, and C_3 are obtained by substituting in equation (3) the three pairs of numbers (T_{min}, V_{max}), (T_{max}, V_{min}), (T_{nom}, V_{nom}) and solving the resulting three simultaneous linear equations.

The derived time to fly, T_d, can now be substituted into equation (3) to obtain an estimate of the correct descent speed. Next, the actual time to fly corresponding to the estimated descent speed is calculated by the forward-backward synthesis method. Experience with this algorithm has shown that for a 120-n.-mi.-long trajectory with a nominal flight time of 1,300 sec, the descent speed estimate obtained from equation (3) will achieve an actual arrival time within ±5 sec of the desired time in most cases. This accuracy is adequate for terminal area time scheduling. If the initial speed estimate using equation (3) gives insufficient time accuracy, one can iterate a second time by using the results of the first trial to update the polynominal coefficients. The range of arrival times for the example in figure 1 is 220 sec. A larger range, if needed, can be obtained by flightpath modifications such as path stretching.

GROUND BASED FLOW MANAGEMENT SYSTEM

Time Scheduling in the Mixed Environment

The 4D-equipped aircraft described in the previous section have the capability of meeting a touchdown-time assignment to an accuracy of a few seconds. It is now desired to use this capability to formulate efficient operational procedures for the time scheduling of all aircraft in the terminal area. This will be developed in three parts: (1) determine the inter-arrival time separations for two consecutive aircraft to be used in aircraft scheduling; (2) develop a scheduling algorithm for assigning landing times; and (3) develop a speed advisory system to help the controller nullify time errors of unequipped aircraft. The speed advisories are generated by the ground computer automatically, but can be altered as necessary by the controller.

Time Separation Requirements

The present ATC system uses radar vectors and speed control to space aircraft so that the minimum separation distance rules are not violated. The minimum separation distance rules depend on aircraft weight category, and are summarized in figure 2. For example, if a small aircraft is in trail following a large aircraft in the landing sequence, these two aircraft must be separated by at least 4 n. mi. during the entire length of the common flightpath.

		TRAILING AIRCRAFT		
		SMALL	LARGE	HEAVY
FIRST TO LAND	SMALL	3	3	3
	LARGE	4	3	3
	HEAVY	6	5	4

Figure 2.– Minimum separation distance, n. mi.

These minimum separation distances can be converted to minimum separation times using speed profile data. Suppose that a large aircraft and a small aircraft use the same runway and have a 5.1-n.-mi. common path length on the final approach. The large aircraft is traveling at 180 knots, and at the outer marker (located 3.1 n. mi. from touchdown) begins its deceleration (at 2 ft/sec^2) to a final speed of 135 knots. The final speed for the low-performance aircraft is 110 knots. This information is summarized in figure 3. If the large aircraft lands first, the minimum separation distance occurs at the beginning of the common path. Using this information, the minimum separation time at touchdown can be computed to be 138 sec. With this separation *time*, the minimum separation *distance* requirement will not be violated at any point along the common path. In this fashion, assuming the speed profile for the heavy aircraft is the same as that shown for the large aircraft, the minimum time separation matrix is that found in figure 4.

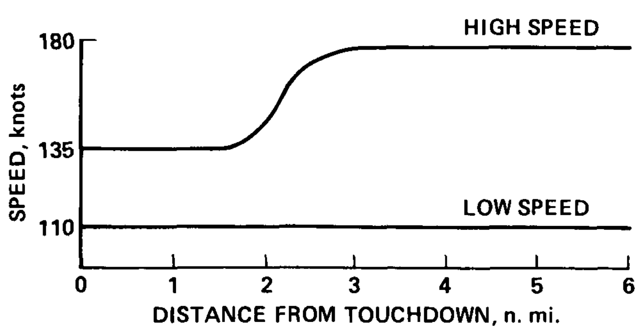


Figure 3.– Speed profiles.

		TRAILING AIRCRAFT		
		SMALL	LARGE	HEAVY
FIRST TO LAND	SMALL	98	74	74
	LARGE	138	74	74
	HEAVY	167	114	94

Figure 4.– Minimum separation time, sec.

It is assumed that, for two 4D-equipped consecutive aircraft, the interarrival times can be used for scheduling purposes. However, unequipped aircraft will need additional time buffers to prevent separation distance violations. If the probability density function of an unequipped aircraft meeting an assigned time via controller vectoring is known (this can be determined in the specific experimental context), then time buffers can be determined to keep the probability of a separation distance violation below a desired level. The technique for obtaining these buffers is discussed in reference 11. For this study it was assumed that if one of the two consecutive aircraft was unequipped, a 10-sec buffer was added to the separation time. If both aircraft were unequipped, a 20-sec buffer was added.

SCHEDULING ALGORITHMS

Based on knowledge of the feeder fix departure time and on the desired time to traverse the route, a desired touchdown time for each aircraft can be determined. Using this first-come, first-served order and the time-separation matrix developed in the previous section, the time schedule at touchdown is obtained. It is possible to increase capacity by altering the first-come, first-served order, and thus future studies will incorporate time-slot-shifting algorithms to take advantage of bunching of speed classes (ref. 12). However, for purposes of this initial study of operational procedures, the first-come, first-served order is adequate.

In addition to setting up an initial schedule, algorithms are required to revise the schedule. Missed approaches need to be accommodated. Also, the controller may need to change the aircraft arrival rate. It may be that he or she is also required to block out specific time periods from the computer schedule to accommodate a missed approach or a priority landing. In addition, he or she may require that a few aircraft be scheduled in a specific order. This may be accomplished by manipulating the existing schedule. For example, this will be illustrated using the halt procedure. Suppose that an initial schedule has been established for those aircraft that have departed the feeder fix (denoted active aircraft) and those which have not yet departed the feeder fix (denoted inactive aircraft). Controllers may need to hold the inactive aircraft for a time t_h to accommodate a missed approach. A rescheduling algorithm is required which leaves the time assignments for the active aircraft unaltered, but which revises the touchdown times of inactive aircraft by at least t_h. This procedure can lead to a reordering of the schedule. Figure 5 illustrates a typical revision. For illustrative purposes, aircraft are assumed to be scheduled 2 min apart. The effect of the missed approach is to leave active aircraft untouched, but to revise the inactive aircraft schedule by 2–4 min.

Speed Advisory System

In the scheduling process, all 4D-equipped or unequipped aircraft are assigned a touchdown time. For the 4D-equipped aircraft, this time assignment generated by ATC is transmitted to the aircraft which uses its on-board 4D system to land at the assigned time. However, unequipped aircraft must be controlled by vectors and speed clearances. It is up to the controller to issue these clearances so as to meet the assigned time. However, in the arrival sector, from 120 n. mi. to 30 n. mi. from touchdown, the controller is not able to accurately predict spacing conflicts that will occur at the merge point of the various traffic flows; therefore, he or she cannot effectively participate in the ordering and spacing process. Thus, all such vectoring is performed during the last 25-30 n. mi. of flight. Although this method controls traffic successfully, it demands high skill from and gives a large workload to the final controller. Furthermore, fuel is wasted and runway capacity is lost by the limitations inherent in concentrating ordering and spacing control within the confined airspace region close to airports. Thus, an algorithm was developed to give the arrival controller the ability to participate effectively in the spacing.

The intent of the speed advisory system was to derandomize and coordinate the traffic flow from various directions before the final control sector. With inputs of desired landing time, current position, altitude, and speed, the speed advisory system computes and displays the CAS that is required to have the aircraft land at the desired landing time. The arrival controller, who is presented with a table of speed advisories on his or her display, is responsible for issuing the advisories to pilots as early as possible in the descent. As an aircraft descends, the speed advisory system continuously compares the predicted position with the actual position of the aircraft along its projected flightpath to track the time error. If the error exceeds a specified limit at any time in the descent, ±20 sec in this case, the speed advisory system updates the speed advisory shown on the controller's display about once per minute. The update feature makes it possible to control the increase of time errors caused by uncertain winds and other disturbances and to pilot tracking inaccuracies. It gives the controller the flexibility to scan the display and issue the speed advisories during a less busy time period. After the hand-off to the final controller has occurred (about 30 n. mi. from touchdown), the speed advisories are removed from the controller's display. Then, the final controller uses conventional vectoring techniques to make needed spacing adjustments in the final approach area.

INITIAL SCHEDULE (* = ACTIVE AIRCRAFT)		EVENT:	REVISED SCHEDULED (* = ACTIVE AIRCRAFT)	
AIRCRAFT ID	SCHEDULED TOUCHDOWN TIME (HRS : MIN)	A1 EXECUTES A MISSED APPROACH.	AIRCRAFT ID	SCHEDULED TOUCHDOWN TIME (HRS : MIN)
A1*	9:06	CONTROLLER ISSUES	B1*	9:08
B1*	9:08		C1*	9:10
C1*	9:10	HALT FOR	D1*	9:12
D1*	9:12		A1*	9:14
E1	9:14	T_h = 2 MIN	F1*	9:16
F1*	9:16		E1	9:18
G1	9:18		G1	9:20

Figure 5.– Sample scheduling revision.

SIMULATION FACILITY

The simulations were conducted using the NASA Ames Research Center ATC Simulation Facility. It includes two air traffic controller positions, each having its own color computer graphics display; one was designated arrival control and the other was designated final control. In proximity to the color displays, there was a keyboard with which the ATC-display-related requests were entered into the controller displays and the simulation computer; such inputs included changing the position of an aircraft identification tag, transferring an aircraft between controllers, or stopping and restarting the flow of traffic at the feeder fixes.

Each keyboard pilot position can control up to 10 computer-generated aircraft simultaneously. The clearance vocabulary includes standard heading, speed, and altitude clearances as well as special clearances for 4D-equipped aircraft. In this study, three keyboard positions were used; one was responsible for all aircraft in the arrival sector, the other two divided responsibility for aircraft in the final sector. Previous studies have utilized one or two piloted simulators which were connected by voice and data link to the ATC Simulation Facility; however, in this study, no piloted simulator was used. It is planned to include an airline quality simulator as well as a helicopter simulator in future studies of the mixed environment.

SCENARIO

The simulated terminal area is based on the John F. Kennedy (JFK) International Airport, New York. The route structure and runway configuration investigated are shown in figure 6. It is assumed that IFR conditions prevail, and that all aircraft use runway 4R; furthermore, no departure flights, winds, or navigation errors are simulated. Two routes, Ellis, from the north, and Sates, from the south, are high-altitude routes flown by large or heavy jet transport aircraft. Aircraft on these routes fly profile-descent fuel-conservative procedures, but may either be equipped or unequipped with the 4D system. Hence, there is a mix of 4D-equipped and unequipped aircraft of the same speed class on the same route. Low-performance aircraft fly the Deerpark route from the east, but use the same final approach and land on the same runway as the jet traffic. The Deerpark traffic is unequipped, and always constitutes 25% of the traffic mix.

During this study, an extended terminal area was considered. Aircraft entered the extended terminal area at the feeder fix points, and were at a cruise speed and altitude. The total distance to be flown along each of the jet routes was 120 n. mi. and that flown by low-speed aircraft was 60 n. mi. Two air traffic controller positions were established, arrival control and final control. The arrival controller controlled

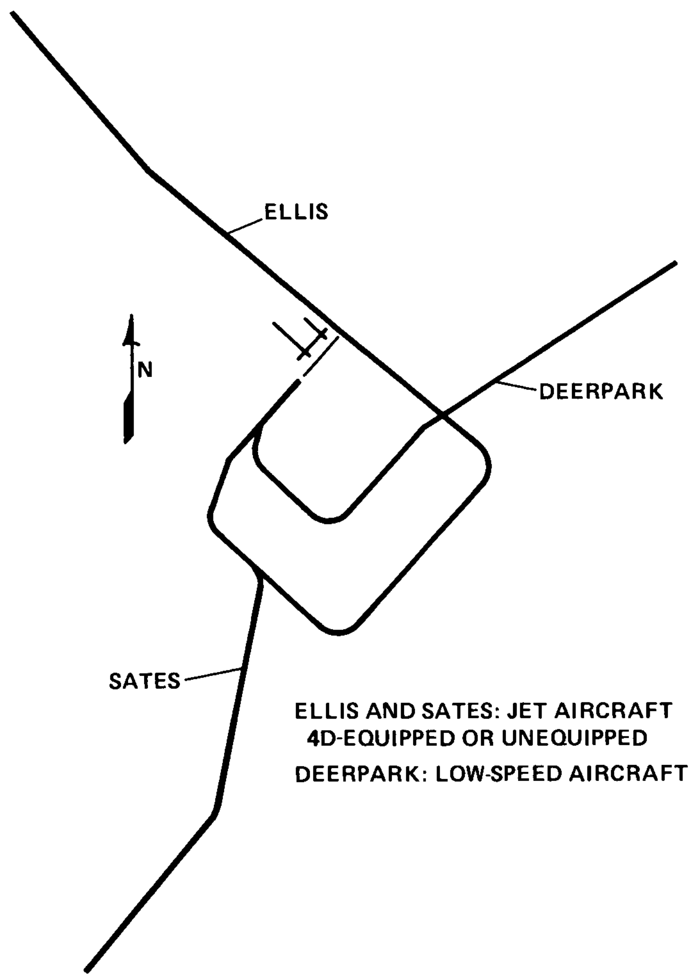


Figure 6.– Route structure.

aircraft from all three feeder fixes and transferred traffic to the final controller at approximately 30 n. mi. from touchdown.

Control procedures differed for equipped and unequipped aircraft. Controllers were instructed to monitor the progress of 4D-equipped aircraft after the time assignment had been established, and to override the ground computer scheduling system only if necessary for ATC purposes. Any 4D-equipped aircraft could also be controlled by conventional methods and treated as unequipped. Alternatively, a 4D-equipped aircraft which had been taken off the 4D route could be given a waypoint to recapture a 4D route, and be given a revised landing time. Unequipped aircraft were considered to be navigating in the conventional manner via very high-frequency omnidirectional radar (VOR) procedures, with altitude clearances, radar vectors, and speed control.

To assist the controller in integrating the 4D-equipped and unequipped traffic, a flight data table was provided on each controller display. A typical arrival controller display is shown in figure 7. The map portion of the display provides a horizontal display of traffic in the terminal area. Each aircraft position is shown by a triangular symbol and the block of data next to each aircraft indicates the aircraft identification, type, altitude and speed. The flight data table, in the upper left portion of the display, provides schedule information for all aircraft in the approach control sector. At the top of the table, the time is shown in hours, minutes, and seconds. The first column shows the aircraft identification, such as "R1." The second column provides aircraft type (TYPE) which includes (1) weight category: small (s), large (blank), or heavy (H), and (2) 4D status, equipped (4) or unequipped (U). The third column provides the assigned route (RT). Also shown is the scheduled time of arrival (STA) at the runway in minutes and seconds. Thus, R1 is scheduled to touchdown at 13:37:00. Note that touchdown times are shown for all aircraft, 4D-equipped or unequipped. For the 4D-equipped aircraft, this is the time assigned by the ground-based computer system to touchdown. For the unequipped aircraft, no time assignment is given to the aircraft; rather the controller is to use this information, the positions of the 4D-equipped aircraft as they traverse their routes, and the speed advisories to generate appropriate vectors to the unequipped aircraft so that they touch down at the time indicated. The next column is the expected delay (DY), where the expected delay at touchdown is in seconds. For some of the data runs, it was assumed that all aircraft departed the feeder fix at their scheduled departure times. This assumes the existence of an advanced en-route metering system. In the absence of such a system, large feeder fix departure errors may occur for unequipped aircraft. Thus for the balance of the runs, unequipped aircraft were assumed to depart with an initial time error uniformly distributed in the range ±120 sec.[1] Thus, if an aircraft departed the feeder fix 90 sec late, a DY of 90 would be displayed, indicating that unless controller action was taken, the aircraft would touch down 90 sec late. Early arrivals were indicated by a negative value in the DY column; late arrivals by a positive value. All 4D-equipped aircraft departed the feeder fix at the scheduled departure time. In flight tests it has been shown that 4D-equipped aircraft can meet time schedules within ±5 sec (hence, these small errors were neglected) (refs. 3 and 4).

The calibrated airspeed (in knots) is shown in the CAS column. This is the ground-computer-generated speed advisory discussed earlier, which assists the controller in nullifying the feeder fix departure error. Details of how the advisory is generated can be found in reference 13.

Once the CAS advisory is issued, the pilot adjusts the speed accordingly, the gap between the reference position

[1] These delays are considered large since, for example, two consecutive unequipped aircraft could arrive in the final control sector in reversed order if there are consecutive departure errors of +60 sec and -60 sec. Also, some informal testing of controllers by the FAA in the en-route area indicated that with practice, controllers could get aircraft over a designated arrival fix within ±1 min of an assigned time, without any computer-generated assistance.

13 : 27 : 12

ID	TYPE	RT	STA	DY	CAS
R1	4	SA	3700	0	
I1	H4	SA	3824	0	
L2	SU	DP	4131	−50	115
J1	U	EL	4305	35	260
T1	4	SA	4429	0	
A2	HU	EL	4715	−80	230
E2	U	SA	4929	120	290*
M2	HU	EL	5103	100	280
G2	H4	SA	5247	2849	

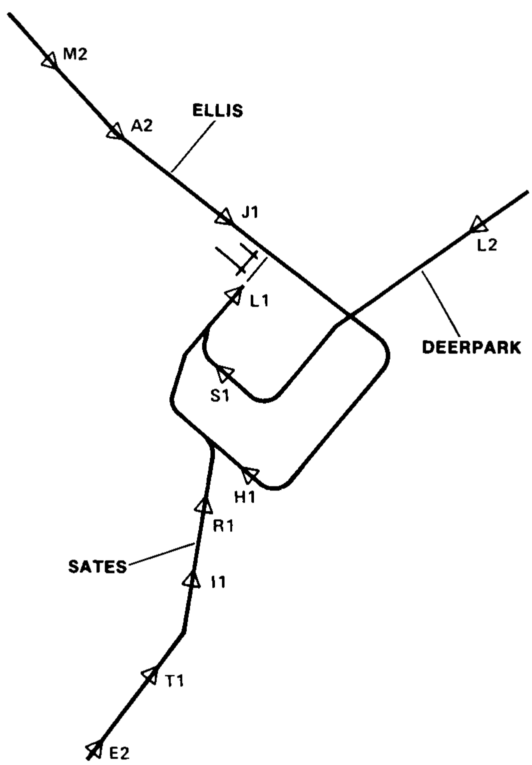


Figure 7.– Typical arrival control display.

and the actual aircraft position narrows, and the magnitude of the delay is reduced. Since errors are incorporated into the aircraft speed-command input, the delay (DY) may not be reduced to zero. However, if the magnitude of the delay is less than 20 sec, then the CAS advisory is removed; this discourages excessive use of the advisory to nullify small errors which the final controller can readily resolve.

It is also possible to provide other controller assists in addition to or in place of the one or more CAS clearances just described. One example is to provide the final controller with an advisory of when to turn an aircraft from downwind to base leg; other options are yet to be investigated. The choice of the CAS advisory used in this study was based on two factors: (1) only one type of advisory was to be provided to minimize additional controller workload, and (2) the advisory would be issued in the arrival sector so that the time errors could be reduced by the time the final control sector was reached. If this advisory was successful, the final controller would receive aircraft in the proper sequence with only minor adjustment remaining. Otherwise, considerable radar vectoring and perhaps resequencing might be required in the final control area. It should be noted that if large feeder fix departure errors occur, it may be more desirable under some circumstances not to readjust aircraft via a CAS advisory to return to the initial touchdown schedule; instead, the schedule might be readjusted. This will be considered in future studies.

Finally, aircraft below the dotted line in figure 7 are aircraft which will depart the feeder fix within the next 5 min (under DY) indicated by the feeder fix departure time in minutes and seconds.

TEST CONDITIONS

The main variable was the traffic mix. In the case with no feeder fix departure errors, three mix cases were run: 25%, 50%, and 75% 4D-equipped aircraft. In addition, baseline data were also obtained for the 0% 4D-equipped case; i.e., when all aircraft use radar vectoring. For the case of 50% 4D-equipped aircraft, two formats were used for the information in the flight data table. The first is the standard display format discussed previously, but without the CAS column. The second format had no time information displayed in the flight data table for the unequipped aircraft. Unequipped aircraft were merely listed in departure order beneath the time-ordered list of 4D-equipped aircraft.

In the case where feeder fix departure errors were present, three mixes were run: 0%, 25%, and 50% 4D-equipped aircraft.[2] In these cases, the time information and advisory, that is, STA, DY, and CAS, were displayed in the flight data table. In addition, simulation runs were conducted for the 0% case when STA, DY, and CAS were not displayed. This corresponds to present operations.

In addition to the main test cases, some special runs were conducted to get a minimum amount of data on other issues of interest, which, because of the time constraints of real-time testing, could not be considered as main variables. In the runs with no feeder fix departure errors, two special cases were considered. The first case examined the effect that a breakdown of the 4D-scheduling computer might have on the controlling of traffic. This was investigated by the removal of the flight data table from the controllers' displays during a 75% 4D-equipped run. Controllers were then no longer provided with time schedules or approach sequence for aircraft in their sector. Furthermore, all feeder fix departures from then on would not have any 4D time assignment, and would have to be controlled by conventional methods. The map display, which showed aircraft positions, was not removed. The second case examined operations at higher arrival rates for the conventional control mode. During main test runs, a time separation buffer of 20 sec was assumed to be added to the minimum separation time for each pair of unequipped arrivals; this resulted in a capacity of about 30 aircraft/hr. For all 4D-equipped aircraft with no buffers added, the capacity would be 37 aircraft/hr. In two special runs, the separation buffers were dropped to see if conventional control procedures would be feasible at the higher arrival rate. In two special runs when 25% of the traffic was 4D-equipped and the unequipped aircraft departed with initial time errors, controllers were restricted in controlling unequipped aircraft as well as leaving 4D-equipped aircraft on the established path unless absolutely necessary for ATC purposes. It was requested that in the final control sector they keep all unequipped aircraft on the same flightpaths as the 4D-equipped aircraft; thus, spacing between aircraft had to be achieved entirely by speed control.

The aircraft arrival rate into the terminal area was assumed to be high enough so that a full schedule with no gaps was generated. The arrival rate for the baseline mode was 30 aircraft/hr and varied up to 34 aircraft/hr for the 75% case. The lower "full schedule" arrival rate for the 0% 4D case is due to the time separation buffers added for the unequipped aircraft.

No departure traffic was simulated, nor were winds or navigation errors considered. These will be included in future investigations. However, they are not expected to alter significantly the general procedures discussed here.

Fifty-four data runs were made in all, each 80 min long. Three air traffic controllers from the FAA Technical Center, Atlantic City, participated in these studies.

[2]In this series of runs, the main feature was feeder fix errors for unequipped aircraft and the 75% 4D-equipped case was not of sufficient interest to merit additional data runs, so the 75% 4D-equipped case was not considered.

RESULTS AND DISCUSSION

Controller Evaluations

Quantitative data were obtained from controller verbal evaluations recorded after each data run, and from controller written evaluations obtained after the completion of all the runs. Controllers were asked to compare operations under the traffic mix conditions. The 25% 4D-equipped case was rated the condition with the heaviest workload. The main difficulty seemed to be that the controllers were establishing distance spacing for the majority of the traffic, and they felt that by not altering the flightpath of the 4D-equipped aircraft, they were occasionally losing some slot time. However, they were quite pleased with the 50% 4D-equipped case, which allowed for easy control of the unequipped aircraft. One controller commented that it was the best ratio; he could "work without being overtaxed." In this mode, fewer communications are required, the traffic flow is more orderly, and it is easy to fill the gaps between the 4D-equipped and the unequipped aircraft.

The 75% 4D-equipped case was rated most orderly by all the controllers, but for this number of 4D-equipped aircraft (the only unequipped aircraft were the Deerpark arrivals, which always constituted 25% of the traffic sample), there was "basically nothing to do." The human-factors issues associated with a high level of ATC automation is a major topic which cannot be dealt with here because of limited realism in the controller operating positions; this subject is dealt with in a comprehensive paper by Hopkin (ref. 14). Finally, the baseline case, when 0% of the aircraft were equipped with the 4D guidance system, was regarded as reasonable, but not because of a lessening of workload; rather, because it was the most familiar.

The controllers were asked if there was any difficulty in controlling the mix of speed classes – the slow traffic from Deerpark and the jet traffic from Ellis and Sates. They indicated that spacing behind the low-performance aircraft was sometimes a problem, since they had to allow for a large initial separation along the common path length. Also, one controller indicated that when controlling a slow-flying aircraft, he was reluctant to extend the downwind leg since this would result in a larger common flightpath with the jet traffic. Hence, the airspace was somewhat restrictive for the slower traffic. No difficulties were indicated in spacing the high-speed equipped aircraft and high-speed unequipped aircraft along the same jet route.

The controllers were provided with time scheduling information in the flight data table. The table was a time-ordered listing of traffic in each sector; also touchdown times and expected delays were provided for each aircraft. The controllers indicated that the only information they used was the time-ordered listing from which the relative order of traffic on the downwind leg and the traffic from Sates was determined. Using this information, and by not altering the 4D-equipped aircraft, controllers were able to radar-vector the unequipped aircraft to their assigned landing slots. However, the touchdown time and delay information was not used. Based on observations, standard radar-vectoring techniques for the unequipped aircraft were adequate to "fine tune" the spacing between aircraft. For the conditions of the experiment, there was not much need to alter initial schedules; however, if considerable interactive schedule manipulation is required, it then seems that a separate controller position for flow control and scheduling is needed. There is not sufficient time for the arrival and final controllers to visually monitor traffic and to monitor numerical time scheduling information simultaneously. The use of a flow control position is consistent with both the present and near-term ATC systems which use flow controller positions for metering traffic.

Controllers compared workload with no feeder fix departure errors with the same mix conditions in which feeder fix departure errors were introduced for the unequipped aircraft. They agreed that when no errors were present, the workload was reduced. However, with the errors present and the speed advisory displayed, the addition of errors was considered workable, and "not a burden."

If the controller uses the computer-generated speed advisory for the unequipped aircraft, the delay is usually reduced. However, since errors of up to ±10 knots are added to any pseudopilot command, the delay may not always be reduced to zero. Controllers compared operations with and without the speed advisory, and evaluated the format and operational procedures established for the advisory. They commented that without the delay or advisory information displayed and with large feeder fix departure errors present, the system yielded "traffic surges." Speed advisories resulted in less bunching of traffic and fewer "ties" in the merging area. With the advisory, the controllers said that the data run seemed much smoother, and that the traffic seemed to blend together and require fewer vectors.

There were some criticisms of the implementation of the speed advisory as it was used in the study. The controllers suggested, for example, that the advisory should be in increments of 10 knots instead of the 5-knot increments that were used. Also, once an advisory was issued, controllers felt it would be useful to indicate this on the flight data table. Occasionally they issued a second advisory to an aircraft when they forgot it had already been issued. Controllers indicated that if the above features could be improved, "advisories would be welcomed in the field."

Controller Workload

The number of clearances issued will be the index used to measure controller workload, and will be compared as a function of mix condition and whether or not there were feeder fix departure errors. Table 1 shows the average number of clearances per aircraft and whether or not there were feeder fix departure errors. The average number of heading, speed, and altitude clearances is shown; the total number of these clearances is also provided.

It can be seen that as there are more 4D-equipped aircraft, the average number of clearances per aircraft decreases. This is fairly obvious in the experiment context described, since 4D-equipped aircraft were generally not issued any vectors. The concern is whether or not the average number of clearances for the *unequipped* increase as the percentage of equipped traffic increases. The answer in provided in table 2, which shows the average number of clearances per aircraft for the Deerpark traffic only. Recall that the Deerpark traffic was always 25% of the traffic sample, and that all Deerpark traffic consists of low-performance unequipped aircraft. The table indicates that the average number of clearances given to the Deerpark unequipped aircraft remain the same, independent of the mix condition. Also shown is the average time in the system (in minutes) for the Deerpark traffic, which is also seen to be independent of the mix condition. Similar results were obtained for Sates and Ellis unequipped traffic. Thus, the total workload reduction as the percentage of 4D-equipped aircraft increased (table 1) was not obtained by additional clearances and delays for the unequipped aircraft.

Next, it was desired to compare controller workload when feeder fix departure errors were and were not present. Since the established procedure was to issue a speed advisory to correct for feeder fix departure errors, table 1 indicates that when feeder fix departure errors were present additional clearances in the form of speed adjustments were issued to each aircraft. However, according to the controller evaluations previously discussed, this additional workload was acceptable because the additional speed clearances were issued by the approach controller who was not busy. Also, as the percentage of 4D-equipped aircraft increased, the average number of clearances decreased, whether or not feeder fix departure errors were included. This indicates that the 0% 4D-equipped case resulted in the highest workload condition; however, controller evaluations consistently indicated that

TABLE 1.– AVERAGE NUMBER OF CLEARANCES PER AIRCRAFT

Four dimensional equipped, %	Departure errors	Average number of clearances/aircraft			
		Heading	Speed	Altitude	Total
0	No	2.7	1.3	1.2	5.2
25	No	2.2	1.2	1.1	4.5
50	No	1.3	.7	.7	2.7
75	No	1.2	.6	.6	2.4
0	Yes	2.5	3.4	1.2	7.1
25	Yes	2.1	2.4	1.0	5.5
50	Yes	1.1	1.4	.6	3.1

TABLE 2.– DEERPARK ROUTE: CLEARANCES AND TIME IN THE SYSTEM WITH NO DEPARTURE ERRORS

Four dimensional equipped, %	Average number of clearances per aircraft				Average time in system, min:sec
	Heading	Speed	Altitude	Total	
0	3.3	1.8	1.8	6.9	19:16
25	2.9	1.8	1.8	6.5	18:56
50	2.8	1.7	1.7	6.2	19:05
75	2.9	1.8	1.7	6.4	19:05

the mix of 25% 4D-equipped aircraft is a higher workload case. The primary reason was that the procedures required controllers not to alter the positions of the 4D-equipped aircraft unless it was absolutely necessary. However, the on-board 4D algorithms are sufficiently flexible so that the controller could, if he or she chose, alter the trajectories of the 4D-equipped aircraft. Hence, future studies will consider dropping the restriction on altering schedules of 4D-equipped aircraft in the final control airspace. This should make the controller evaluation and the data on clearances issued more consistent for the condition of 25% 4D-equipped aircraft.

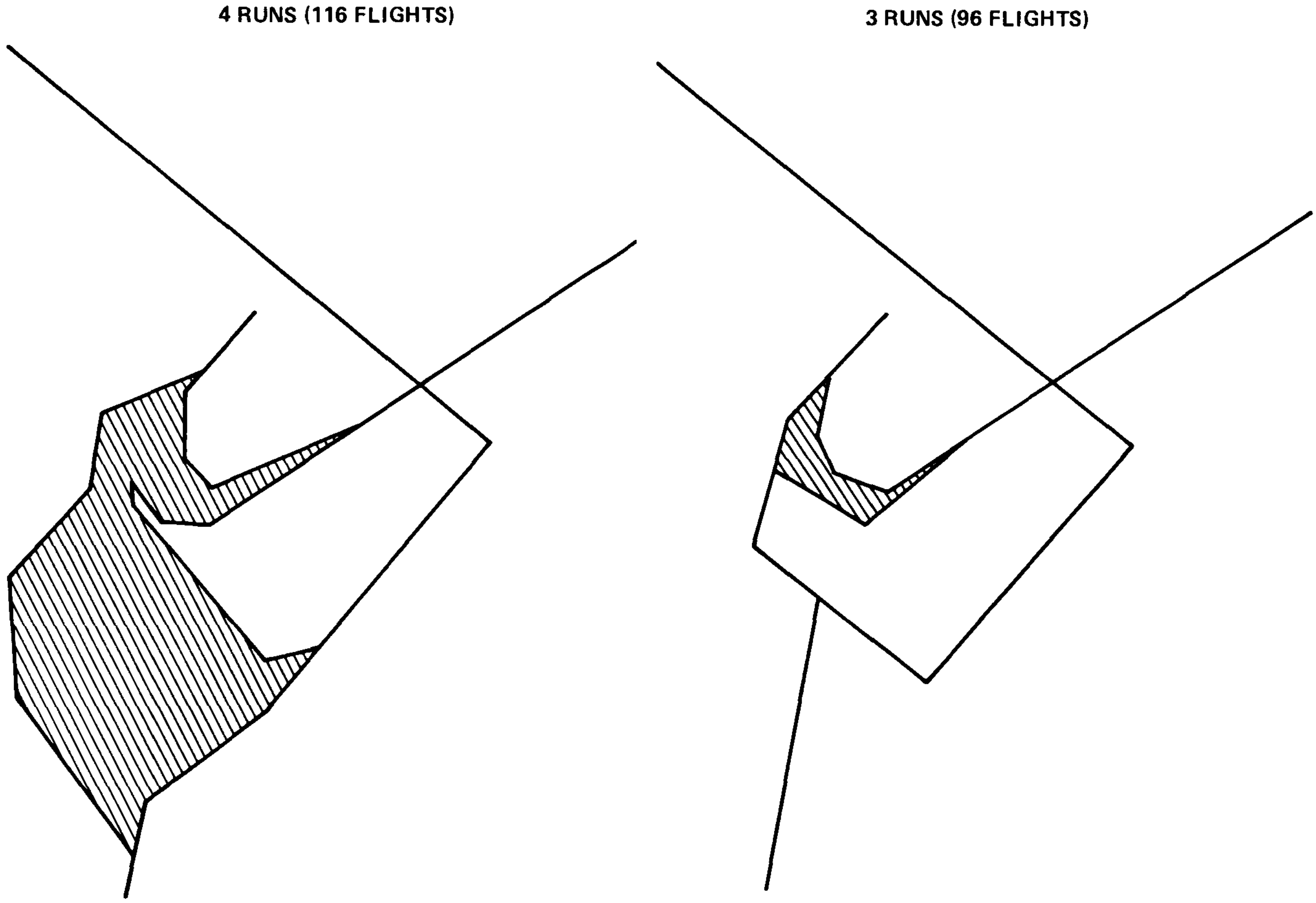
Airspace Used

A comparison was made of the airspace used in 0% 4D-equipped runs and 75% 4D-equipped runs, all without feeder fix departure errors. Figure 8(a) is an envelope plot of all 116 flights flown in the four runs conducted in the baseline 0% 4D-equipped mode. For each aircraft, an *x-y* plot was drawn. The individual *x-y* plot shows the trajectory that aircraft followed from feeder fix entry until touchdown on the runway. Figure 8(b) is the corresponding plot for the 96 flights flown in the 75% 4D-equipped case. In the latter plot, the only region used for path-stretching is the base leg of the Deerpark route. By contrast, the baseline mode required a large area because of extensive path-stretching. The 4D operations permit the equipped aircraft to fly a more orderly, fuel-efficient pattern, and to reduce considerably the airspace required for each flightpath.

Special Case Runs

In addition to the main test case where the variable was the percentage of 4D-equipped aircraft, a minimum amount of data was collected (namely one or two runs each) for a variety of other variables. Some of these are briefly described here.

Loss of 4D– Initially, there was no change when the flight data table was removed from each controller's display. The



(a) 0% 4D-equipped.

(b) 75% 4D-equipped.

Figure 8.– Airspace used.

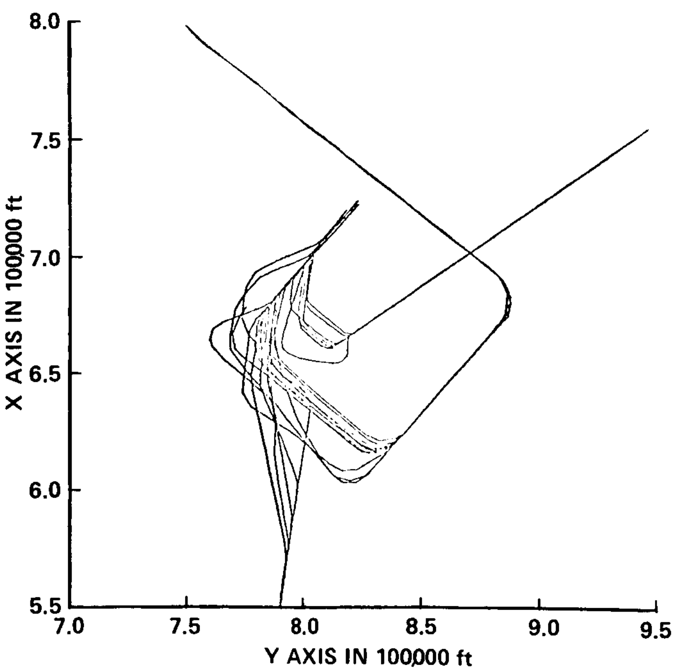
4D-equipped aircraft already in the control sector could still be left alone since they would continue to follow their previously assigned 4D route. This is in contrast to a totally ground-based 4D system where the ground system generates clearances for each aircraft; when that type of system fails, all aircraft are affected in a short time. The only difficulty experienced with the system as tested was that after the failure occurred, controllers continued to allow traffic to depart the feeder fixes at the higher arrival rate for the 75% 4D-equipped case, rather than to adjust to the baseline 0% arrival rate. If the flow rate adjustment for new feeder fix departures is made when the failure occurs, then it seems clear that the use of the on-board 4D system provides a safe transition to conventional methods of control.

Conventional control operations and capacity– Data from these special runs in which time separation buffers were removed, indicated that it was necessary to delay arrivals at the feeder fix, and that more airspace was used for controlling traffic. It was determined that the landing rate was about the same as it was without the buffers. Thus, the limitation of the maximum arrival rate via the time buffers was reasonable; otherwise, capacity would have to be reduced by the controllers via holding and/or path-stretching delays. Thus, the addition of 4D-equipped aircraft reduces the buffers and increases capacity.

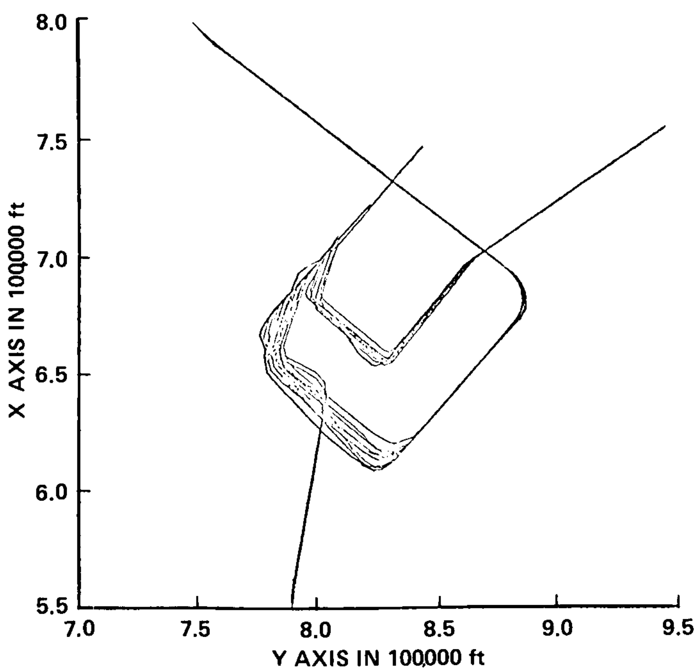
Aircraft following exact routes– Controllers were initially hesitant when asked to keep unequipped aircraft on specified flightpaths, but after an initial trial period with speed adjustments only, they said it seemed to go well. In the conventional mode, controllers use a region of airspace and issue radar vectors to accomplish final spacing between aircraft. This is illustrated in figure 9(a), which is a composite plot of the 30 flightpaths flown in a typical data run using 25% 4D-equipped aircraft. A typical composite plot for the special case in which unequipped aircraft followed exact routes is given in figure 9(b) where it is seen that considerably less airspace was required to accommodate the same number of aircraft. The plot indicates that control of unequipped aircraft in a 4D environment can be restricted to specified horizontal routes. This is an area for future investigation.

CONCLUSIONS

Algorithms were developed for controlling a mix of 4D-equipped and unequipped aircraft in the terminal area. Operational procedures were developed to obtain an initial time schedule and to provide for revisions to this time schedule for this mix of aircraft. In addition, the effect of time errors at the feeder fix departure on the controller's ability to maintain a time schedule for aircraft at touchdown was investigated. An effective operational procedure was developed which provided speed advisories to the air traffic



(a) Typical 25% 4D-equipped run.



(b) 25% 4D-equipped following exact routes.

Figure 9.– Composite plot.

controller for aircraft whose expected touchdown time deviated significantly from a desired schedule.

The basic rule established for handling a mix of 4D-equipped and unequipped aircraft along the same route and for mixing different speed classes along merging routes was not to alter the 4D-equipped aircraft once they were assigned a landing time. This procedure resulted in the controllers learning to use the 4D-equipped aircraft positions to effectively vector the unequipped aircraft to their assigned landing slot. In addition, in a special set of runs it was shown that a loss of the ground-based 4D system results in a smooth transition to vector operations.

An approach controller's use of a speed advisory, which essentially requires a 4D computation by the ground computer, enabled deviations from assigned touchdown time to be reduced so that by the time the aircraft entered the final control sector, the final controller could handle the traffic in the same manner as when there were no large initial errors. Additional work was required of the arrival controller in the form of a speed advisory, but this was not considered burdensome. Thus, time errors by unequipped aircraft at the feeder fix can be handled so that they do not disrupt a desired time schedule for the 4D-equipped aircraft.

Controller evaluations indicated that the 25% 4D-equipped case was the most difficult to handle. Nevertheless, quantitative data actually showed a decrease in the number of controller clearances with respect to the 0% 4D-equipped case. Controllers felt that the procedure of not altering the 4D-equipped aircraft when so few were equipped was workable, but was a more complex task.

The controller workload as measured by the average number of clearances per aircraft decreased as the percentage of 4D-equipped aircraft increased. Moreover, this average decrease was not accomplished at the expense of the unequipped aircraft. The number of clearances for the unequipped aircraft as well as the time delays were independent of mix condition.

Several issues raised indicate the need for further investigation. First, a simulation should be conducted to include a piloted simulator in order to investigate an unequipped aircraft's response to speed advisories, further development of efficient ground-based 4D algorithms for unequipped aircraft, and development of algorithms for optimized revised time schedules. Second, final controller operations should be examined for each of the following conditions: (1) 4D-equipped aircraft can be removed from 4D routes as the controller desires; and (2) unequipped aircraft are constrained to follow the same horizontal routes as the 4D-equipped aircraft.

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National Aeronautics and Space Administration
Moffett Field, California, March 1985

REFERENCES

1. Menga, Giuseppe; and Erzberger, Heinz: Time-Controlled Descent Guidance in Uncertain Winds. J. Guidance and Control, vol. 1, no. 2, 1978, pp. 123-129.

2. Burghart, James T.; and Delanty, Edward A.: Impact of Time-Based Air Traffic Management Procedures on Future Navigation/Guidance. Natl. Aerospace Mtg., Atlantic City, April 1978. Proceedings. Washington, D.C., Inst. Navigation, 1978, pp. 141-147.

3. Lee, Homer Q.; Neuman, Frank; and Hardy, Gordon H.: 4D Area Navigation System Description and Flight Test Results. NASA TN D-7874, 1975.

4. Knox, C. E.: Fuel-Conservative Descents in a Time Based Metering Environment. Proc. 18th IEEE Conf. on Decision and Control, Dec. 1979.

5. Tobias, Leonard; and O'Brien, Paul J.: Real-Time Manned Simulation of Advanced Terminal Area Guidance Concepts for Short-Haul Operations. NASA TN D-8499, 1977.

6. Tobias, Leonard; Palmer, E. A.; and O'Brien, P. J.: Simulation Study of the Effects of Fuel-Conservative Approaches on ATC Procedures and Terminal Area Capacity. Paper no. 780523, Soc. Automat. Eng. Air Transportation Meeting, May 1978.

7. O'Brien, P. J.; Willett, F. M.; and Tobias, L.: Dynamic Air Traffic Control Simulation of Profile-Descent and High-Speed Approach Fuel-Conservation Procedures. FAA-RD-80-12, May 1980.

8. Tobias, L.; Lee, H. Q.; Peach, L. L.; Willett, F. M., Jr.; and O'Brien, P. J.: ATC Simulation of Helicopter IFR Approaches into Major Terminal Areas Using RNAV, MLS and CDTI. NASA TM-81301, 1981.

9. Erzberger, Heinz; and MacLean, John D.: Fuel-Conservative Guidance System for Powered-Lift Aircraft. J. Guidance and Control, vol. 4, no. 3, 1981, pp. 253-261.

10. Lee, Homer Q.; and Erzberger, Heinz: Time-Controlled Descent Guidance Algorithm for Simulation of Advanced ATC Systems. NASA TM-84373, 1983.

11. Tobias. Leonard: Time Scheduling a Mix of 4D Equipped and Unequipped Aircraft. NASA TM-84327, 1983.

12. Dear, Roger G.: Increasing Capacity with Computer-Assisted Decision Making. International Air Transportation Conf., April 1979. Proc. Am. Soc. Civil Engineers, vol. 2, 1979, pp. 519-538.

13. Erzberger, H.; and Chapel, J. D.: Concepts and Algorithms for Terminal Area Traffic Management. Am. Control Conf., June 1984. Proceedings. Am. Automatic Control Council, 1984, vol. 1, pp. 166-173.

14. Hopkin, V. David: Human Factors in Air Traffic Control. AGARDograph no. 275, April 1982. Advis. Group Aerospace Res. and Devel. (France).

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TP-2493		

4. Title and Subtitle	5. Report Date
SIMULATION STUDIES OF TIME-CONTROL PROCEDURES FOR THE ADVANCED AIR TRAFFIC CONTROL SYSTEM	July 1985
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Leonard Tobias, Monica Alcabin, Heinz Erzberger, and Paul J. O'Brien	85010
	10. Work Unit No.
9. Performing Organization Name and Address	T-3309
Ames Research Center Moffett Field, CA 94035	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Paper
National Aeronautics and Space Administration Washington, DC 20546	14. Sponsoring Agency Code 505-36-11

15. Supplementary Notes

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16. Abstract

The problem of mixing aircraft equipped with time-controlled guidance systems and unequipped aircraft in the terminal area has been investigated via a real-time air traffic control simulation. These four-dimensional (4D) guidance systems can predict and control the touchdown time of an aircraft to an accuracy of a few seconds throughout the descent. The objectives of this investigation were to (1) develop scheduling algorithms and operational procedures for various traffic mixes that ranged from 25% to 75% 4D-equipped aircraft; (2) examine the effect of time errors at 120 n. mi. from touchdown on touchdown time scheduling of the various mix conditions; and (3) develop efficient algorithms and procedures to null the initial time errors prior to reaching the final control sector, 30 n. mi. from touchdown. Results indicate substantial reduction in controller workload and an increase in orderliness when more than 25% of the aircraft are equipped with 4D guidance systems; initial random errors of up to ±2 min can be handled via a single speed advisory issued in the arrival control sector, thus avoiding disruption of the time schedule.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Air traffic control Time-control procedures Air traffic control simulation Aircraft time scheduling Four-dimensional navigation	Unclassified - Unlimited Subject Category – 93

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	17	A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161 NASA-Langley, 1985